

# A Laser-Based Diagnostic for Tracing Magnetic Field Lines in Spheromaks and Other Self-Organized Magnetically Confined Plasmas

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**A Laser-based diagnostic for tracing magnetic field lines in spheromaks and other self-organized magnetically confined plasmas**

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**Abstract:**

We are in the process of testing a new technique for measuring the magnetic field-line topology in magnetically confined plasmas. The basic idea behind the FLIRT (Field Line TRacing) diagnostic is to use a high powerful short pulse laser to launch a burst of energetic ( $\sim 100\text{keV}$ ) electrons from a target passing through the plasma of interest; these electrons then generally follow field lines until they strike a solid surface, where a burst of x-rays is produced and then detected. The field line connection length can be determined from the time delay between the laser pulse and the burst of x-rays. The topology of the field lines can be inferred by measuring the connection length as a function of initial target location inside the plasma. Measuring the spatial distribution of the x-ray production will provide further information on the field topology, including the effects of magnetic field fluctuations and stochasticity. The work will eventually include testing the appropriate x-ray detectors, measuring the background x-ray emission in a spheromak plasma, measuring the energetic electron production by a short-pulse high power laser, and making preliminary measurements of the edge field line topology in the Sustained Spheromak Physics Experiment (SSPX) using a newly-designed pulsed electron beam source as a prototype for a laser-based source. This technique may have broad application to a variety of plasma configurations and provide physics data applicable to a wide range of plasma physics problems.

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## 1. Introduction

Cross-field particle and energy transport in plasmas confined by fluctuating or tangled magnetic field configurations is an area of increasing interest to the magnetic fusion community. A number of approaches to magnetic fusion energy research (e.g., the spheromak and the field-reversed configuration) rely on currents within the plasma to self-consistently produce the confining magnetic fields. This process necessarily results in fluctuating magnetic fields and complex magnetic topologies. Similar processes apply to the solar and galactic magnetic fields and the earth's magnetosphere. Understanding particle transport and acceleration in these dynamical systems requires detailed information about the field fluctuations and the global magnetic topology of individual flux tubes; local magnetic field measurements give an incomplete picture. We discuss work directed towards developing a diagnostic technique for characterizing the global magnetic field topology in magnetically confined plasma.

The basic idea is to use short-pulse high intensity lasers to generate energetic electrons ( $E \sim 50\text{--}100\text{keV}$ ) to probe the field topology of a magnetically confined plasmas. The electrons are produced when the laser pulse strikes a solid target such as nearby walls or pellets injected into the plasma. The fast electrons are tied to the magnetic field lines (typical gyroradius is about 0.5cm in a 2kG field for  $E=100\text{keV}$ ) and will move along these lines without collision (experiencing also a slow drift across field lines) until they strike the first wall. By injecting them into the plasma at a known time and location, we can determine the field line length from their flight time, as determined by the hard x-rays produced when they hit the wall. We can gain information about the field line stochasticity (effective spatial diffusion scale length) by the distribution of the strike points over the surface of the vessel and the spread in their arrival times.

Using an intense short pulse laser to generate the fast electrons makes it possible to generate the electrons from either the exterior or interior of the plasma with minimum perturbation. The pulse width is small, providing more than adequate temporal resolution. No large electron gun structures or coaxial feed lines are needed, only optical access to the target area. The target can be either a divertor or limiter plate touching the edge plasma or a small probe or solid pellet of any material injected into the plasma core. Unlike positron-based schemes, plenty of electrons can be produced making detection of the hard x-rays relatively simple.

The main uncertainty in the application of this technique to real plasmas is the efficiency of producing the fast electrons with the laser. It is well known that copious quantities of energetic electrons can be produced efficiently by intense laser beams [1,2,3]. What is not well known is the extraction efficiency for getting these energetic electrons out of the target, optical focusing requirements (can we get a small enough laser spot size on a target with the higher  $f/\#$  optics necessitated by access restrictions of real plasma devices), and space-charge buildup on the target that can limit the extracted current significantly, which then directly affects the laser intensity required to produce the burst of free-streaming electrons. This effect may be mitigated to some extent using an ionizing pre-pulse, though little or no data exists.

In the remainder of this paper we discuss the application of this technique to high temperature laboratory plasmas. We consider the suitability of using fast electrons to trace magnetic field lines in Section 2 and examine some of the features of the field line topology that can be diagnosed. In Section 3 we look at the efficiency of generating fast electrons with a short pulse laser. In Section 4 we discuss detection requirements, while in Section 5 we look at the application of the technique to a spheromak plasma. Finally, in Section 6 we outline the research we are doing to show the feasibility of the technique, using the Sustained Spheromak Physics

Experiment (SSPX) [4] at Lawrence Livermore National Laboratory (LLNL). We include some performance data on a novel insertable electron beam source that will be used to inject electrons, similar in characteristics to the laser-based source, into the edge plasma of SSPX.

## **2. Probing Magnetic Field Topology with Fast Electrons**

To be specific, we discuss here the generation of fast electrons from a target (the projectile in Fig. 1) situated in the plasma. The target is moving very slowly relative to the electron motion and can be considered stationary. A rough time history of the expected signals is shown in Fig. 2 and described here. The first effect that can be observed is a mirror reflection of some of the electrons. Generally, the magnetic field strength varies along the field line and for toroidal devices increases towards the major axis. If the maximum (along the field line) field is higher than the field at the injection point, electrons with large-enough pitch angles will be reflected back. The length of the trajectory for such electrons will be  $\sim \pi R$ , where  $R$  is the chamber radius (Fig. 1), i.e.,  $\sim 1.5$  m for SSPX. These electrons will come back to the target and produce a “prompt” signal, delayed by only  $\sim 15$  ns. Note that some of these electrons will miss the target, because their gyroradius may be larger than the target size. Varying the target size could be another control knob in the proposed experiment.

Another relatively prompt signal will appear if the target is situated near a rational surface, where the field lines (in a perfect geometry) are closed. The field line originating from the target will hit the target again. For small  $m$  and  $n$  numbers (the numbers of poloidal and toroidal rotations the field line makes before closing on itself), the length of the field line is  $\sim 2\pi nR$ . For  $n < 3$ , it is  $\sim 10$  m. Therefore, those electrons that do not experience mirror reflection, will come back to the target in  $\sim 100$  ns. This statement depends on how close the field line

structure is to the ideal one. Some electrons will miss the target and will be involved into the further diffusive motion. The comment about the target size pertains to this case, too.

Finally, if the surface is closed but not rational, the electrons will be involved in a sort of “diffusive” motion in a braided magnetic field. They will hit the wall over the large surface area, comparable to the whole inner surface of the vacuum chamber. The length  $L$  determines the time this will take ( $\sim 100$  m in the example presented in Table 1).

In the limiting case of “open” geometry, the picture will be entirely different. The mirror-reflected electrons may still be present, but the rest of electrons will hit a wall very quickly ( $\sim 10$ - $15$  ns) in a narrow spot (not coinciding with the injection point). As we have already mentioned, stochastic effects may broaden the spot. If a coarse energy resolution proves feasible (e.g., by means of X-ray absorbers of varying thickness), we could collect information related to effects of small-scale turbulence, with the scale  $\sim$  fast electron gyroradius. Generally, deciphering signals in the problem under consideration is similar to the spectroscopic analysis, where shape and position of lines are the carrier of the information.

Fast electrons experience rotation around the field line and magnetic drift; EXB drift is usually unimportant for them. Table 1 illustrates the scale of gyroradii; the gyroradii were evaluated for the full electron energy.

Table 1. Fast electrons in SSPX at B=5 (2) kG, and L=100m\*

Electron energy, keV	Electron velocity, $v$ , $10^{10}$ cm/s	Electron gyroradius, mm	$L/v$ , $\mu$ s $\theta^{**} = 0^\circ$	$L/v$ , $\mu$ s $\theta = 60^\circ$
50	1.4	1.6 (4)	0.7	1.4
100	1.8	2.2 (5.5)	0.53	1.06
250	2.5	3.5 (8.2)	0.4	0.8
500	3	4 (10)	0.33	0.66
1000	3	7 (17.5)	0.33	0.66

\*L is an expected connection length in good confinement regimes

\*\* $\theta$  is electron pitch angle

### 3. Fast Electron Production by Short-pulse Lasers

Ultimately, the laser pulse must generate sufficient electrons to produce a detectable signal in the actual experiment. This minimum number of electrons (and hence, minimum laser intensity), estimated to be of the order of  $10^{10}$ - $10^{12}$  for the experiment here, depending on the sensitivity of the x-ray detectors (view factors and quantum efficiencies) and on the x-ray background produced by the plasma to be studied. We believe this number to be small because the electron temperature is less than 300eV in the SSPX spheromak [5] that we want to diagnose, but we will need to verify this with actual measurements; high energy “runaway” electrons can be produced by inductive fields along toroidal field lines during certain phases of the discharge.

It is well known that high intensity laser pulses can produce large quantities of fast electrons [1,2,3]. However, the fraction of these electrons which actually escape the laser target is not well known and needs to be investigated since the FLIRT signal is produced only by those electrons that escape the target and hit the spheromak wall. We believe that space charge buildup around the target will be the main factor governing the efficiency of fast electron production, though focussing the laser onto the target will be an issue too. The more electrons we need to get off the target to produce a detectable signal, the higher the space charge, which will inevitably mean



increased mean electron energy and laser intensity. A very preliminary study of this effect and finds that, while the space charge effect does drive up the required laser energy, as long as we can live with  $10^{10}$ - $10^{11}$  electrons/pulse, only modest laser pulses are required. However, we need to confirm this with experiments. The presence of a dense ( $\sim 10^{19} \text{ cm}^{-3}$ ), cold blow-off plasma (which could be generated by a pre-pulse) near the surface (a plasma layer should be  $\sim c\tau \sim 300 \text{ }\mu\text{m}$  thick) would help in neutralizing the space charge during the main pulse.

We assume that the characteristic energy of energetic electrons is  $10^5 \text{ eV}$ . This is large enough to produce easy-to-detect X-rays but small enough to keep the gyroradius below  $0.5 \text{ cm}$ , yielding a relatively high spatial resolution. Assuming that the total number of electrons is  $10^{13}$ , we see that their total energy is  $0.16 \text{ J}$ . Assuming that the efficiency of converting the laser beam energy into energetic electrons is  $1\%$ , we see that the total energy per pulse has to be  $16 \text{ J}$ . For  $10^{12}$  fast electrons, the required laser energy would be  $1.6 \text{ J}$ . For  $10^{12}$  electrons, even assuming that they are uniformly distributed over the whole surface area of the experimental volume ( $\sim 4 \cdot 10^4 \text{ cm}^2$ ), we find more than  $10^7 \text{ electrons/cm}^2$ , which should provide comfortable conditions for X-ray measurements.

#### **4. Detection Requirements**

The choice of detector geometry and timing requirements will depend on the temporal and spatial distribution of the relativistic electrons striking the wall. Conversely, what we learn about the magnetic field structure depends somewhat on how well we can correlate these measurements to a model for stochastic field lines in the spheromak. Without making any attempt to specify their type, we formulate here some basic requirements to their performance.

We discuss the case where a stationary target is situated near the wall. The size of the target should probably be somewhat greater than the characteristic gyroradius, so that all the mirror-

reflected electrons be absorbed in one transit (the focal spot may be much smaller than the size of the target), to avoid an additional source of uncertainty in the interpretation. Assuming that the total number of fast electrons in 100 keV range is  $N=10^{12}$ , and that half of them are mirror-reflected, one can expect  $\sim 5 \cdot 10^{11}$  electrons hitting the target within  $\sim 10$  ns. This will produce an easily discernable large signal. If the target happens to coincide with a rational flux surface (to be within fast electron gyroradius from it), a somewhat longer burst will follow,  $\sim 30$  or so ns long. The rest of electrons will experience a diffusion-like motion and produce much longer signal ( $\sim 1\mu\text{s}$ ), more or less uniformly distributed over the walls of the chamber. This scenario corresponds to the presence of relatively good flux surfaces. In the limiting case of an "open" geometry, there may still be a burst from mirror-reflected electrons, but the rest of the pulse will arrive much sooner and be more spatially localized.

Accordingly, it is desirable that the detection system could record time-resolved signals from the target itself, and from the walls of the vacuum chamber. There is no need for a good spatial resolution for X-rays coming from the walls. The main point will be determining the lengths of the trajectories of fast electrons, which can be determined by the temporal dependence of the signal. There will also be a burst of X-rays from the target when the laser pulse initially hits the target. This burst serves as a timing fiducial.

## **5. Application to Spheromak Plasmas**

It is desirable to launch the electrons from arbitrary points inside the plasma without perturbing it. We propose to do this by focusing a short high power laser pulse onto a fast-moving pellet fired through the plasma; the high electric field strength at the focus spot leads to generation of fast electrons. A simpler alternative would be to focus the laser onto a plasma-facing wall to produce the electrons, but the geometry is rather limited in this case: we cannot so

easily probe the interior of the plasma. In the SSPX spheromak, the fast moving pellet is actually part of another diagnostic system [6], called TIP (Transient Internal Probe) which operated by the University of Washington to measure the internal magnetic field amplitude via Faraday rotation. By hitting the pellet with the laser at different times as it passes through the plasma (one pulse per plasma shot) we can probe the field topology from the center out to the edge of the spheromak plasma.

## **6. Feasibility Studies to Prove the Concept**

The following three Sections outline the studies we are carrying out to show the feasibility of the concept on the SSPX device: (a) x-ray detection and background measurements, (b) tests of electron production by intense laser pulses, and (c) study of the expected electron trajectories in stochastic field lines coupled with prototype FLIRT measurements using an insertable electron gun.

We assume that the best way to detect when and where the fast electrons strike the SSPX wall is via k-alpha x-ray fluorescence radiation produced when they strike the tungsten coated walls of the plasma chamber. However, it is also possible to measure electrons directly through detectors mounted in openings in the walls. Direct measurement does not have the losses due to x-ray conversion efficiency (estimated to be less than 1%) and small solid angle of collection for typical detectors. Each approach also is impacted by the presence of the plasma and the requirements for high temperature bakeout in a UHV environment. We are evaluating both approaches. The background x-ray brightness of the SSPX plasma is so far unknown. The brighter the plasma background, the larger the electron pulse (and thus the laser pulse) needed to produce a clean signal. Though we don't expect a large background due to the modest plasma

electron temperature, there may be runaway electrons present during certain phases of the discharge; some early spheromak experiments observed MeV electrons.

We have installed several x-ray detectors on SSPX to measure the intensity and energy spectrum of the x-rays produced in typical plasma discharges. The plasma pulse lasts up to 2msec, with a characteristic timescale of 0.1msec, so very fast detectors are not be needed for these measurements. Both collimated and wide field-of-view detectors will be tested. Depending on the signal levels, we may need to build a reentrant port to bring the detector up close to the diagnostic slot to collect from a larger solid angle. The data we obtain will help determine the minimum laser power and optimal electron energy range to use.

We are currently determining energetic electron production efficiency using the JANUSP laser at LLNL. This laser has a well-diagnosed target chamber and beam qualities. We plan to fully characterize (quantity and energy spectrum) electron production in a realistic geometry which includes a background plasma and magnetic field oblique to the target, as would be encountered in typical laboratory fusion experiments such as SSPX. An electron spectrometer [7] has been constructed to directly measure the energy spectrum of the escaping electrons. Subsequent work will explore the use of an ionizing pre-pulse to provide some space charge neutralization.

We are carrying out a limited test of the concept using a small electron gun (Figure 3) to inject a short pulse (10-50ns) of energetic (50–100keV) electrons into the edge plasma of the SSPX device. We detect these electrons using the fast x-ray detectors planned for the full experiment. Although the presence of the injector hardware in the edge plasma will be perturbing to the plasma, this prototype experiment will let us test the detection scheme and data reduction methods while providing scientifically useful new information about the edge

magnetic field topology in a spheromak without the cost of bringing a high intensity laser to the experiment. Measurements of the electron gun on a test stand have shown suitable pulse widths (20 ns) and energy ( $>80$  keV) sufficient to excite the K-alpha fluorescence on gold targets (x-ray energy of 68.8 keV). The x-rays were detected with a fast scintillator (Bicron BC404) coupled to a fine-mesh photomultiplier tube designed for operation in magnetic fields up to 1 tesla. (Hamamatsu R5924). Details of the electron gun will be presented in future work.

## References

1. G.D. Enright and N.H. Burnett, Physical Review A, 32 (1985) 3578
2. K. B. Wharton, S. P. Hatchett, S. C. Wilks, M. H. Key, J. D. Moody, V. Yanovsky, A. A. Offenberger, B. A. Hammel, M. D. Perry and C. Joshi, Physical Review Letters, 81 (1998) 822
3. G. Malka and J.L Miquel, Phys. Rev. Lett. 77, p75 (1996).
4. E.B. Hooper, et al., Nuclear Fusion 39, 863 (1999).
5. H.S. McLean, et al. Phys Rev Lett, 88, 125004 (2002).
6. C.T. Holcomb, T.R. Jarboe, A.T. Mattick, et al., Bull. Am. Phys. Soc. 45, p245, October 2000.
7. H. Chen, et al., this conference.

## Figure Captions

- Figure 1. Schematic of the FLIRT diagnostic concept. High power ultra-short pulse laser strikes a pellet, projectile, or other object in the plasma and produces electrons, which follow magnetic field lines, eventually striking the outer wall producing x-rays, which are detected.
- Figure 2. In toroidal plasmas with closed flux surfaces, the time-history of X-ray signals will group into four categories.
- Figure 3. An insertable electron gun has been designed to inject electrons at the edge of the SSPX spheromak.
- Figure 4. Testing the electron gun has shown sufficiently narrow pulses of electrons and good x-ray production on high-Z targets.

## Figures

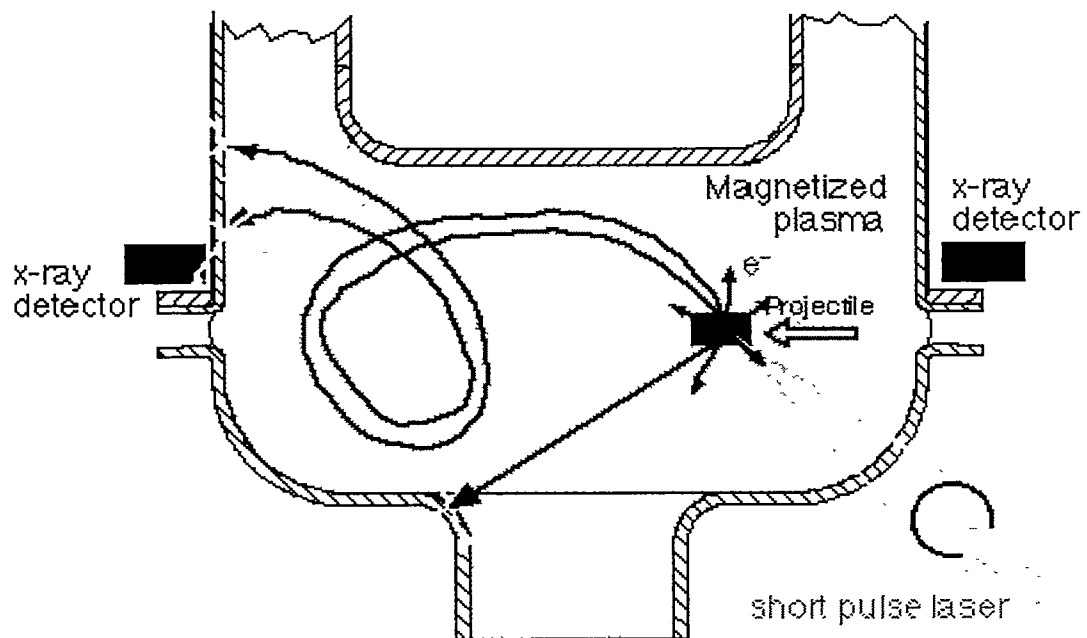


Figure 1

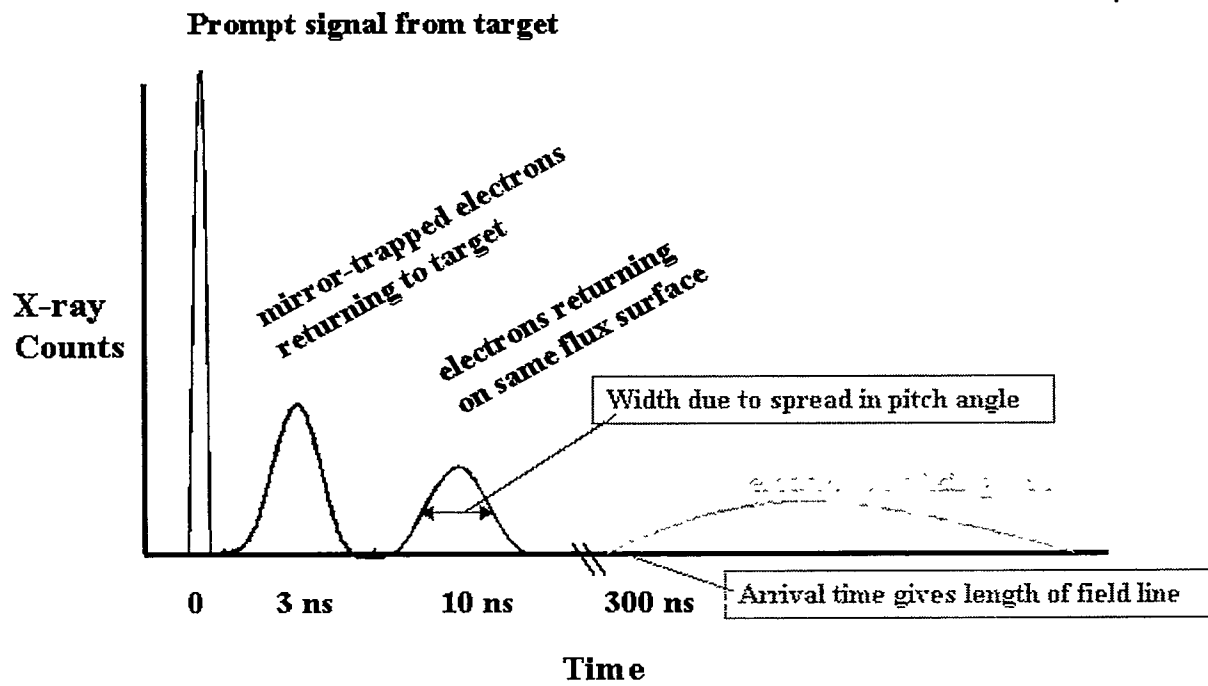


Figure 2



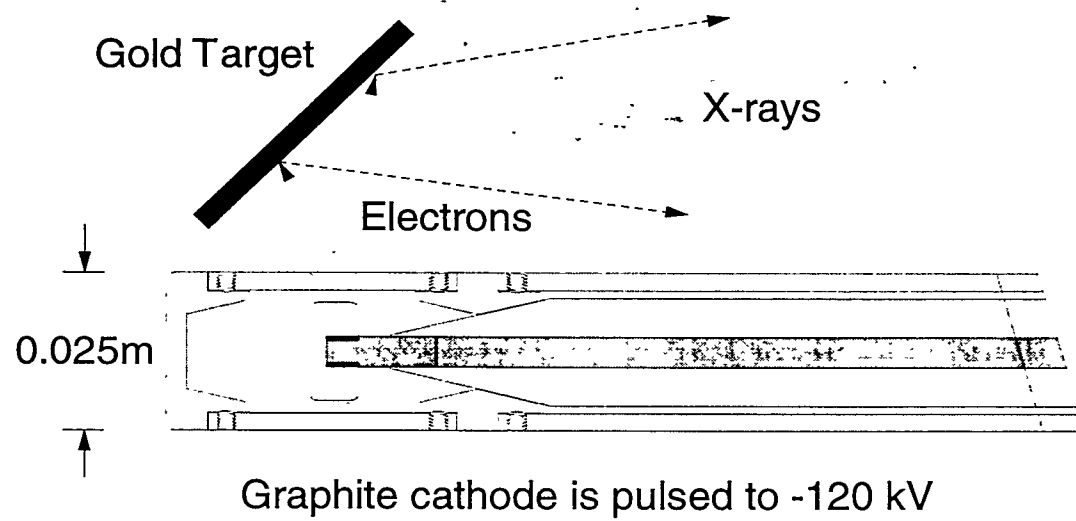


Figure 3

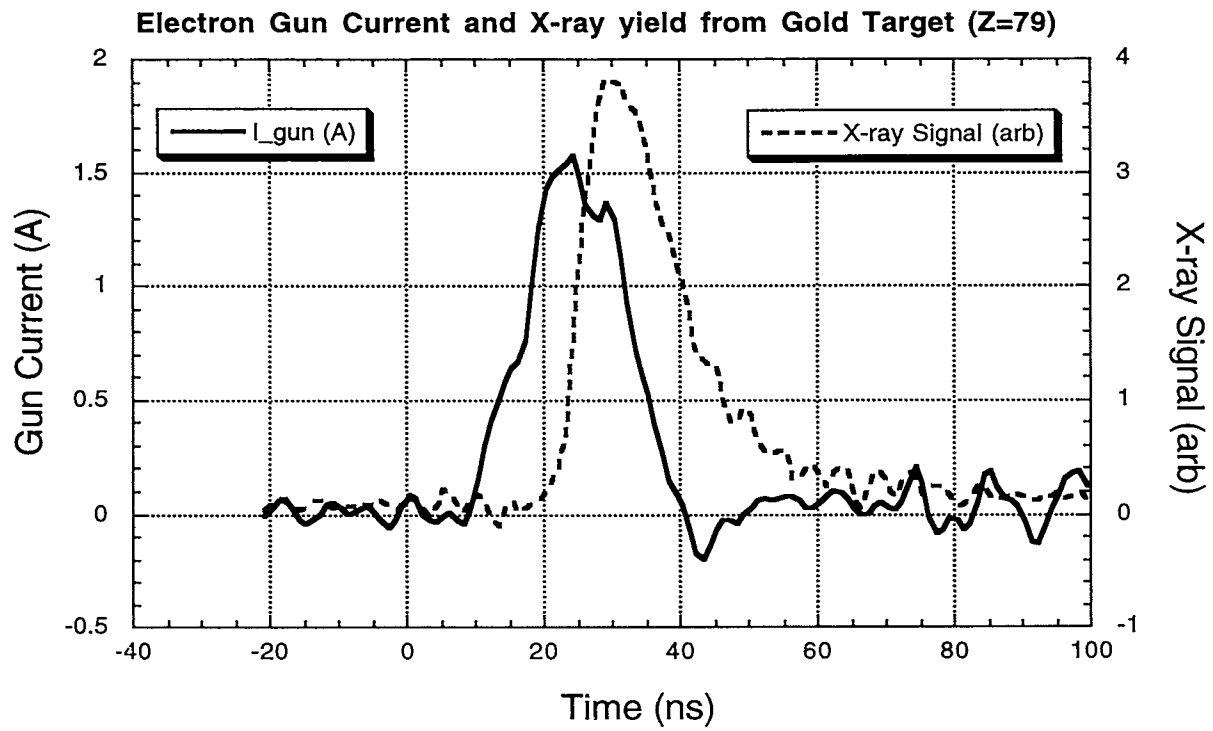


Figure 4